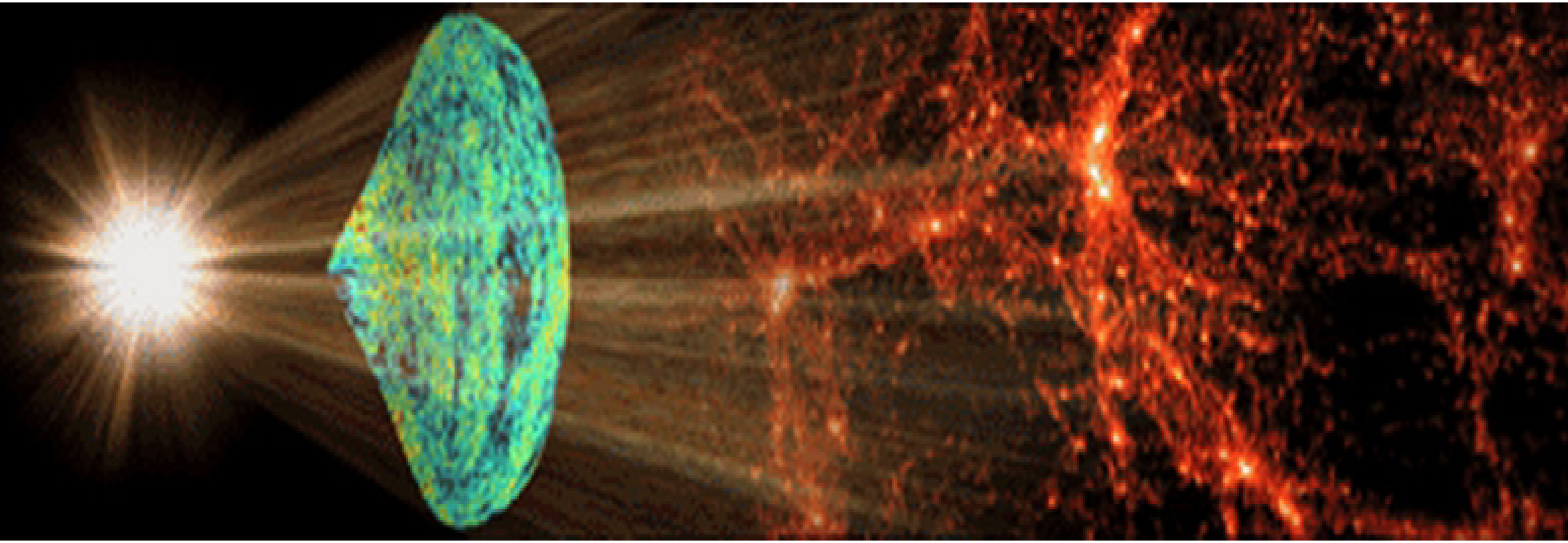
From Spitzer to Herschel and Beyond

The formation of galaxies

Scott C. Chapman

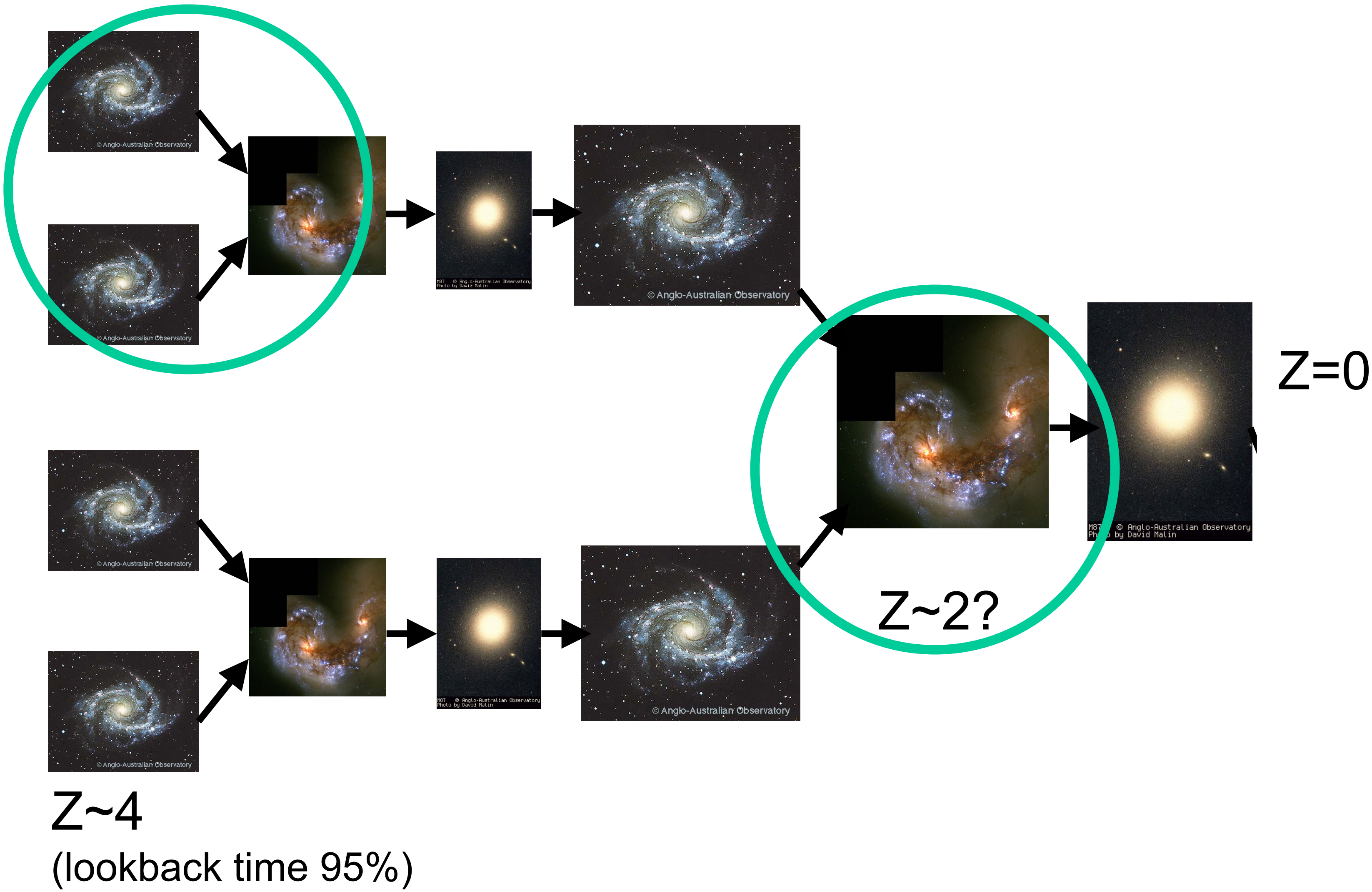
(Caltech)

The *First* Galaxies? (when do most of the stars form?)



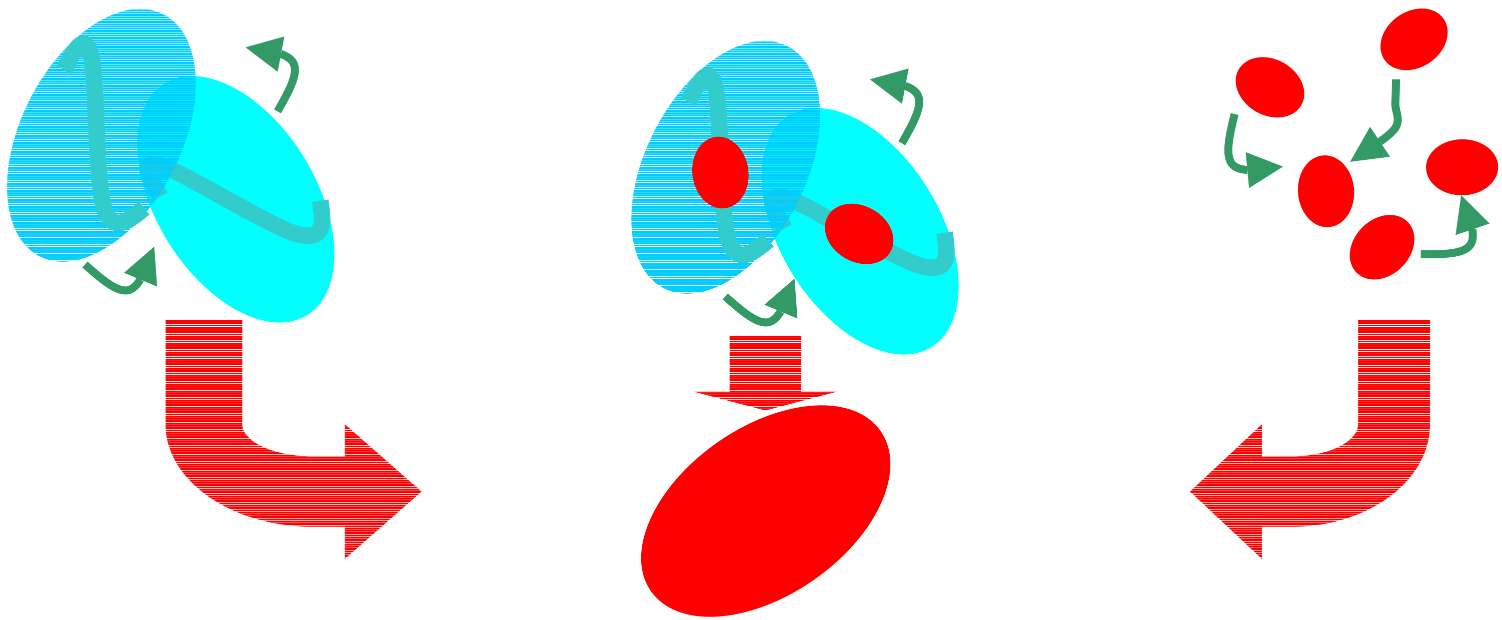
- The most Massive galaxies (>M* ellipticals) form at z~2.3
- Hierarchical Galaxy Formation and Evolution, z~20,5,1,0?
  - non-linear and complicated (hydro, SF, feedback …)
  - Mass may assemble rapidly at certain epochs
  - Luminosity may not couple to Mass

When (and How?) do all the stars get made in galaxies as a function of mass?



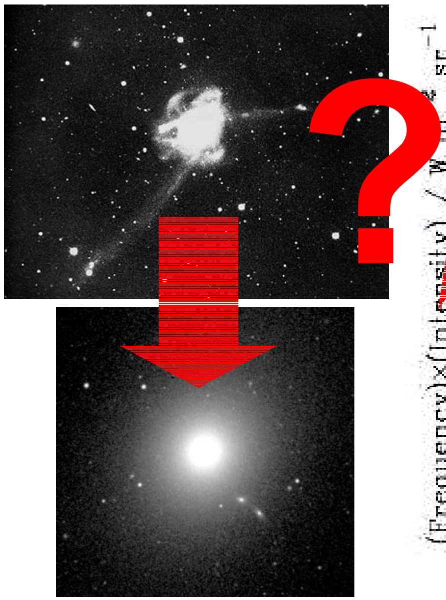
"Form" galaxies quickly during mergers; obscured by dust …

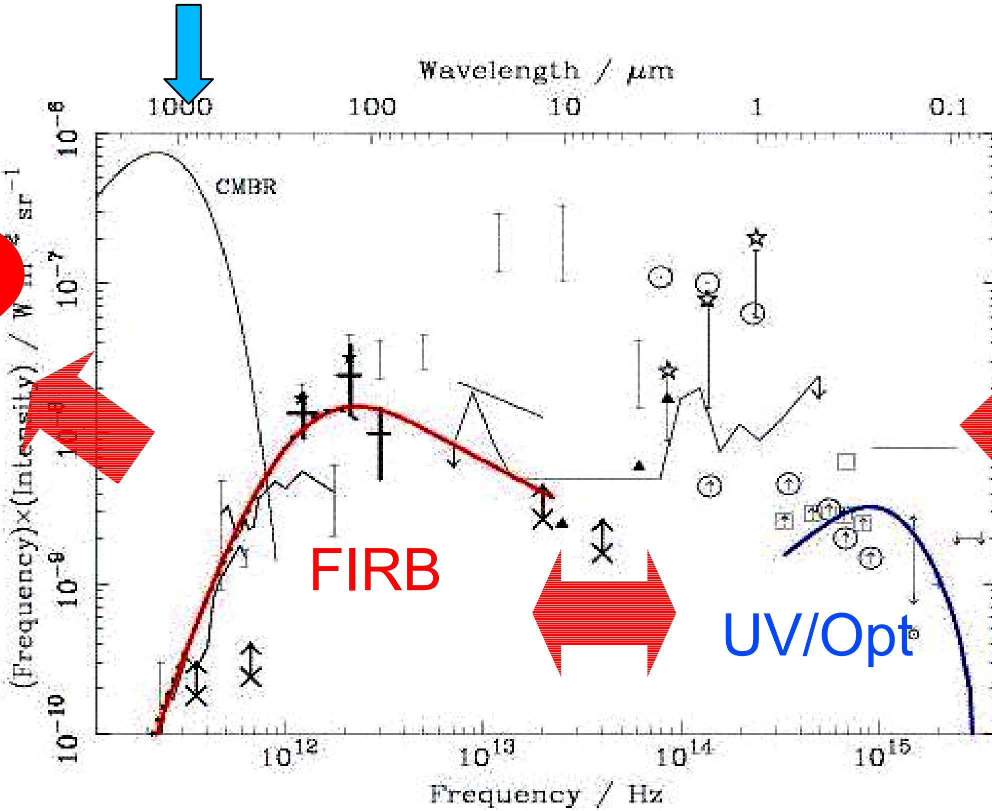
Formation Mechanisms I

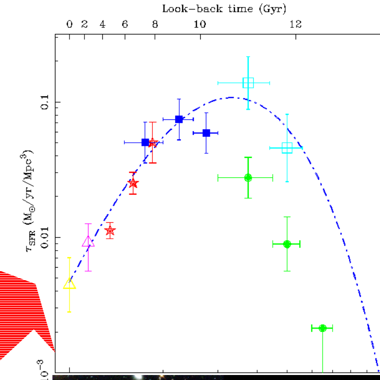


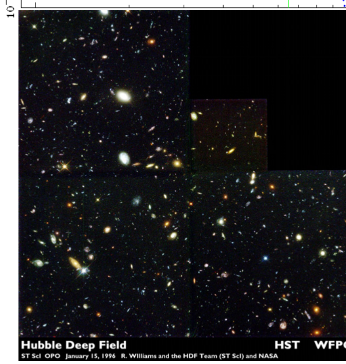
- Wide range of proposed mechanisms for forming massive galaxies:
  - (pseudo-)monolithic collapse ($T_{merge} < T_{SF}$)
  - major merger of two existing galaxies
  - an extended series of minor mergers process ($T_{merge} > T_{SF}$)
- *Can we observationally distinguish between these scenarios?*

The Extragalactic Background









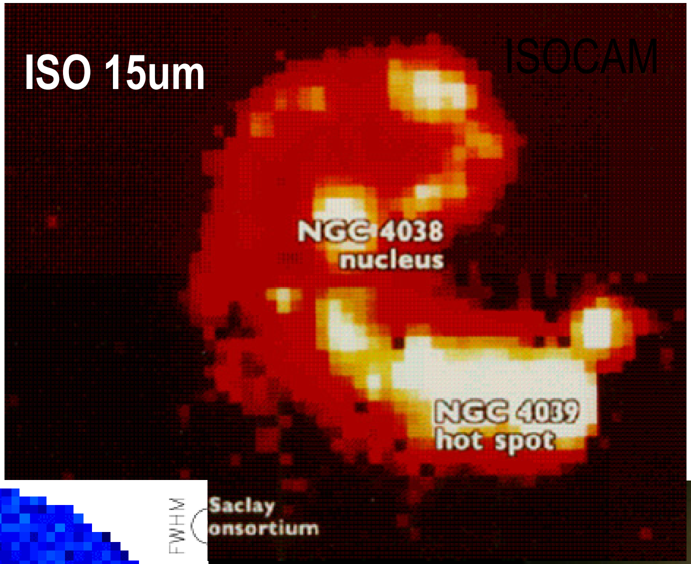
- FIRB = opt/UV EBL -> half of the energy production (from SF or AGN) over history of the Universe arises in highly obscured regions
- Much of the star formation in the Universe might be obscured

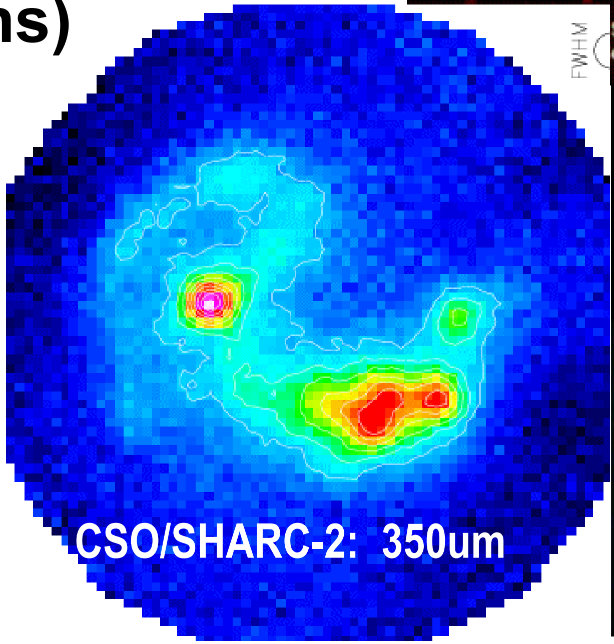
Merging (forming) galaxies: e.g. The Antennae

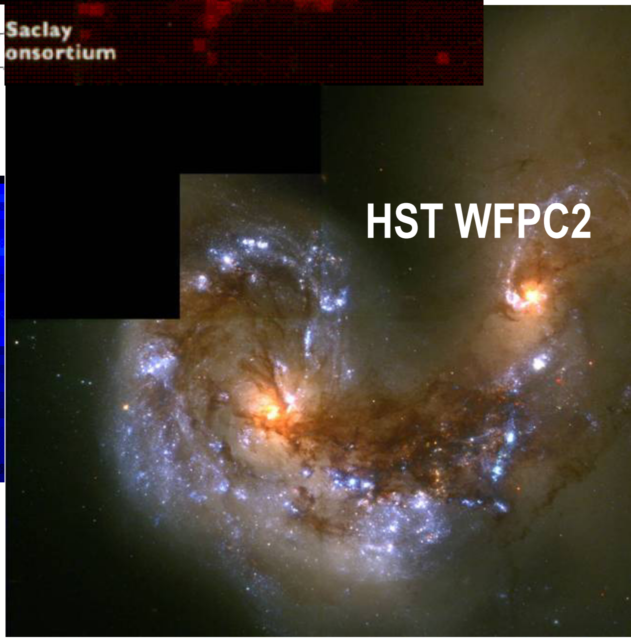
- **Distinct opt/UV and far-IR luminosity**
- **Dust obscures UV;**

  ***absorbs* and *re-radiates* at longer wavelengths**

  (~100-200 microns)



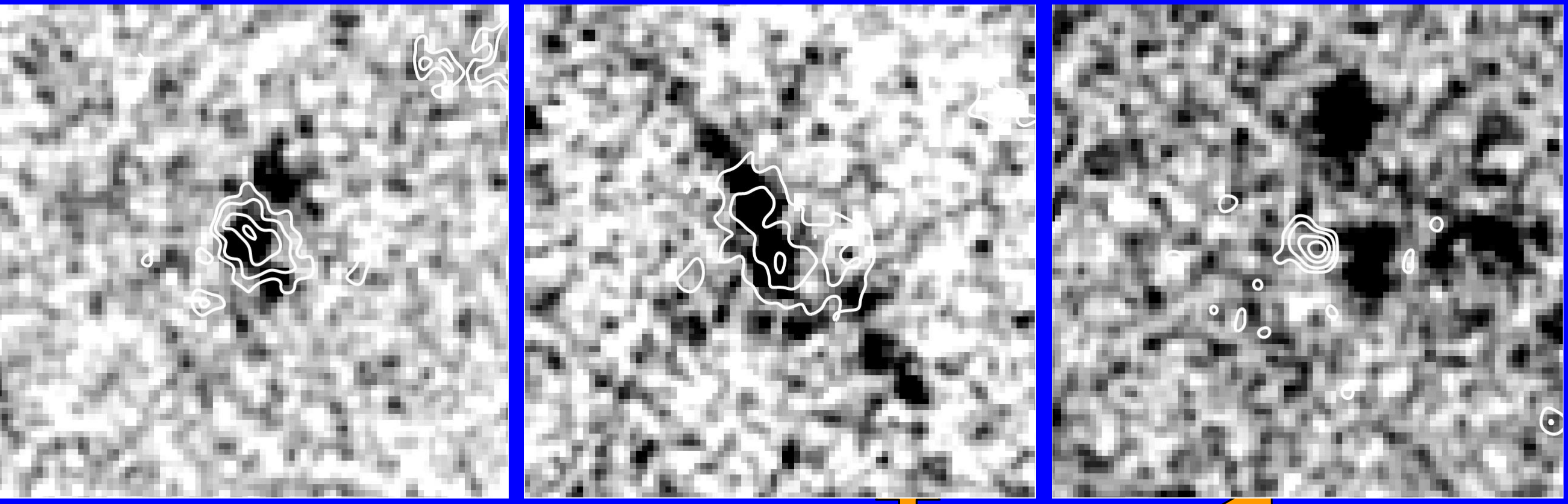




At high-z: Submm Morphologies?
(dust+gas)

Giant Extended (10kpc) starbursts … RADIO tracing UV
(… a very different mode of star formation?)

3" boxes

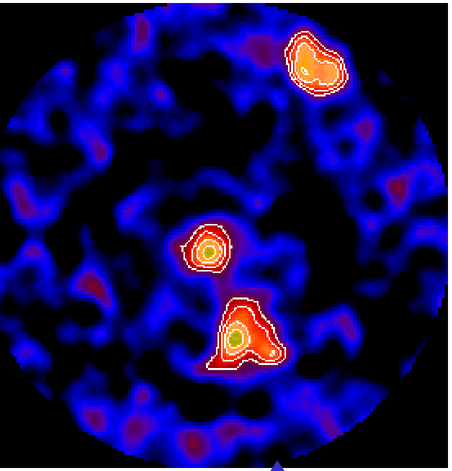


- MERLIN ~0.2 arcsec radio beam
- 65% appear to trace optical structure
- 35% suggest a single compact component
- ~0.4 arcsec RMS accuracy in radio/optical alignment
- Internal obscuration maps …

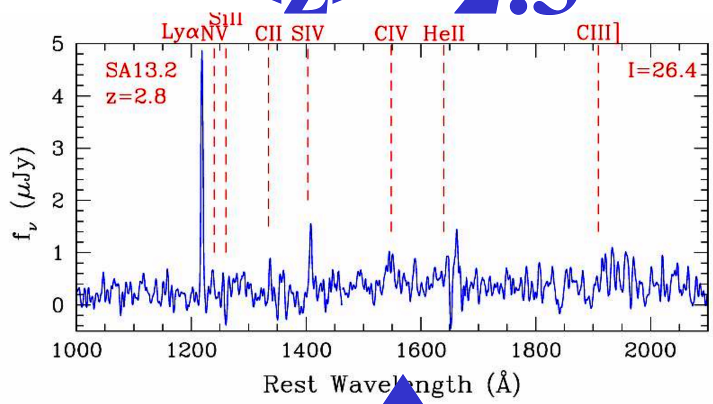
(Chapman,Smail,Windhorst,Muxlow,Ivison 2004)

The birth of massive (>M*) galaxies in the Universe (SMGs)

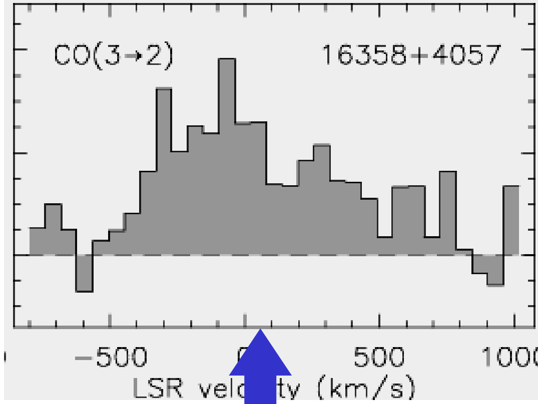
(Chapman,Blain,Smail,Ivison 03,04)

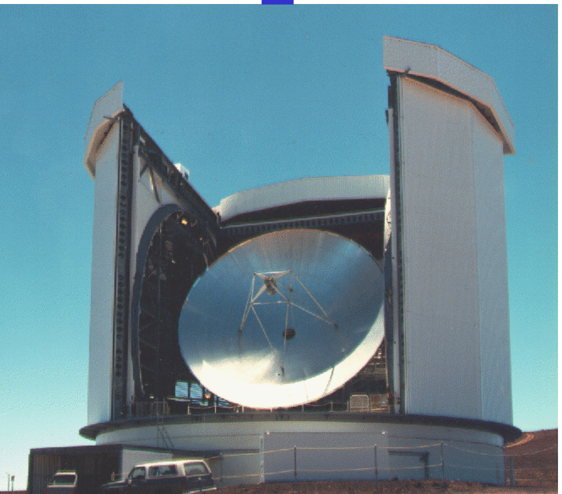


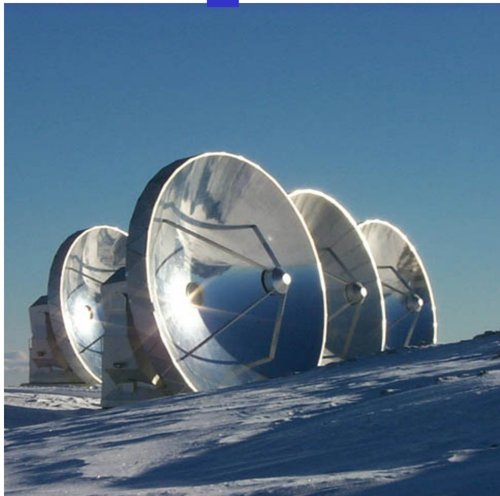
<z>=2.3



massive



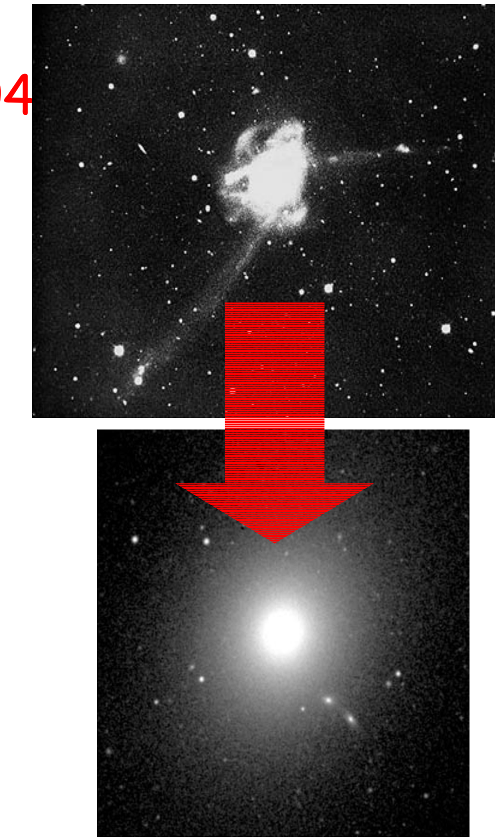




SMGs satisfy Checklist: Proto-Elliptical Population

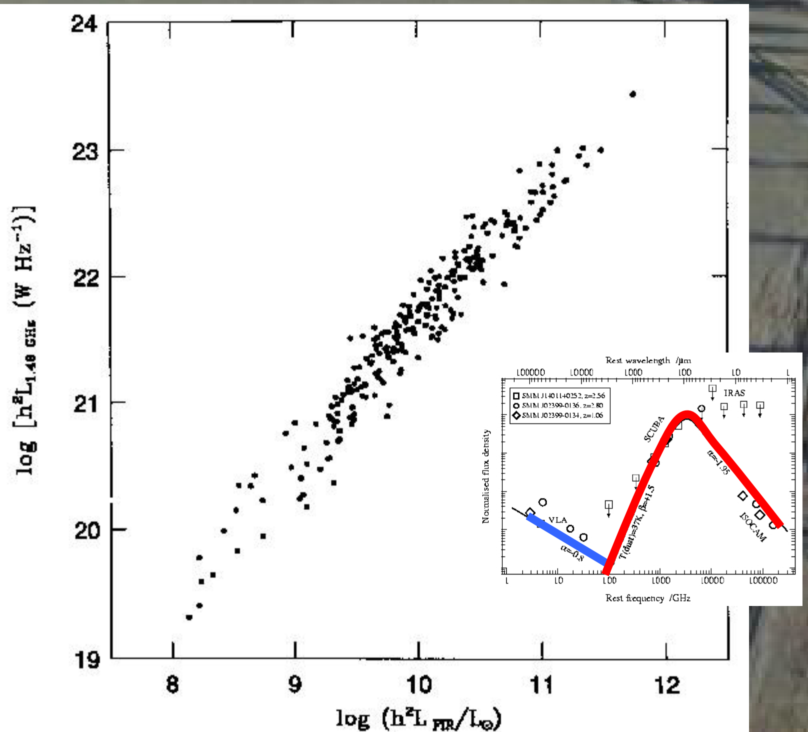
- Contain a significant fraction of SF in the Universe (= large fraction of the EBL)
- Metal rich (dusty, Nii/Hα) (Swinbank+ 04)
- Found predominantly at z>2 (Chapman+ 03,04
- Have a space density $\sim 10^{-5}$Mpc^{3} (few M*)
- Individually exhibit very high star formation rates (Chapman+ 04; Blain+ 04b)
- Have merger-like morphologies
- Host massive black holes (Alexander+ 04)
- Massive galaxies (Frayer+98,99 Neri+ 03)
- Strongly clustered (Blain+ 04b)

-> Local examples - ULIRGs?

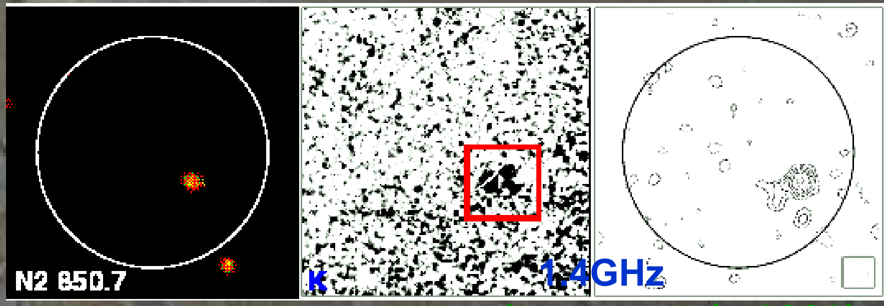


N(z) of SMGs: using the radio to ID

- To make progress …
  - Exploit radio-FIR relation seen for local galaxies (<2x scatter)
  - Pinpoint large samples of SMGs in the radio (0.3″ accuracy)

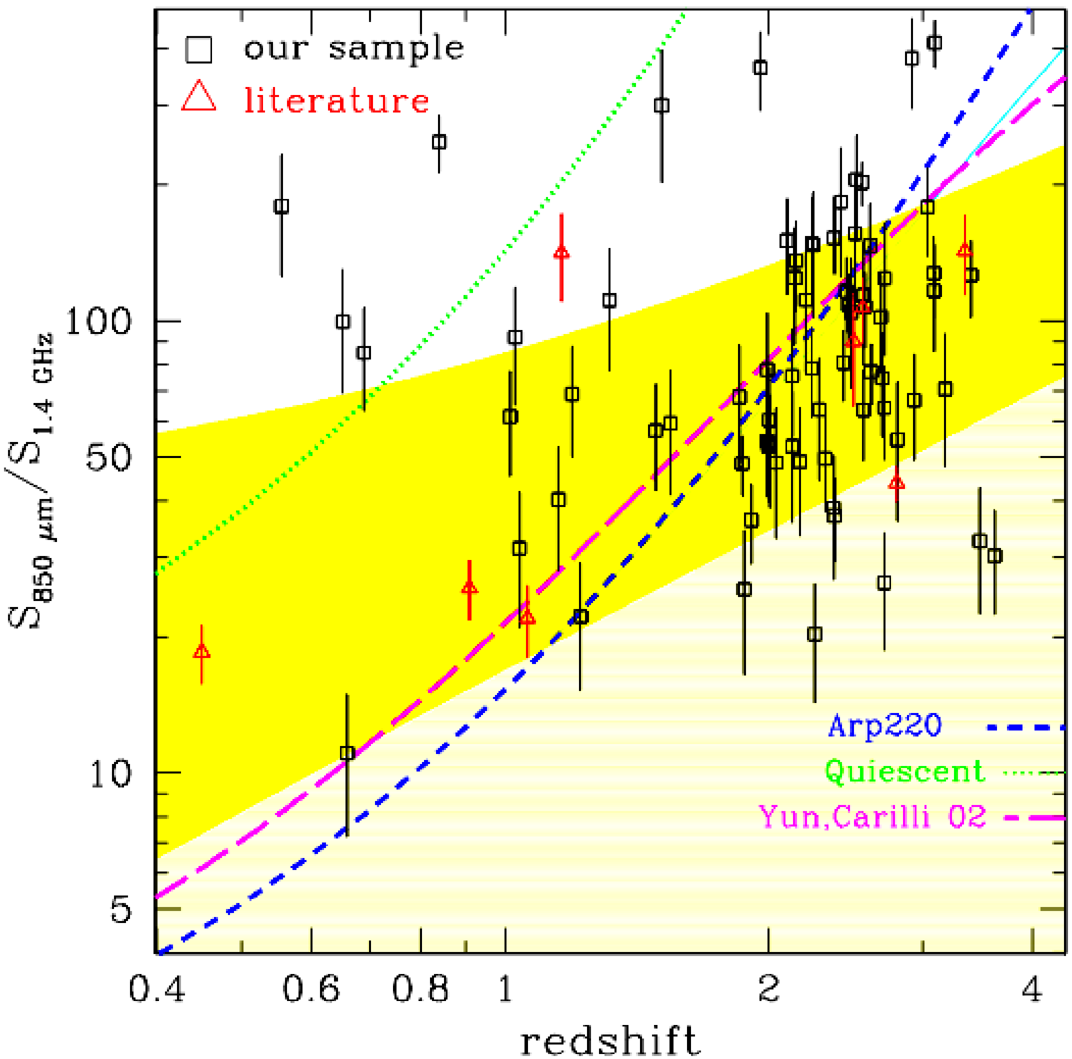


Far-IR correlates with
synchrotron radio
(SNe: shock accelerates cosmic rays)



(Ivison et al. 2002)

Photometric Redshifts for dusty,luminous gals?



Proliferation of Submm/radio redshift indicator

But dz ~ 1

Somewhat better in UV/opt if detectable

Can Spitzer/Herschel help? …

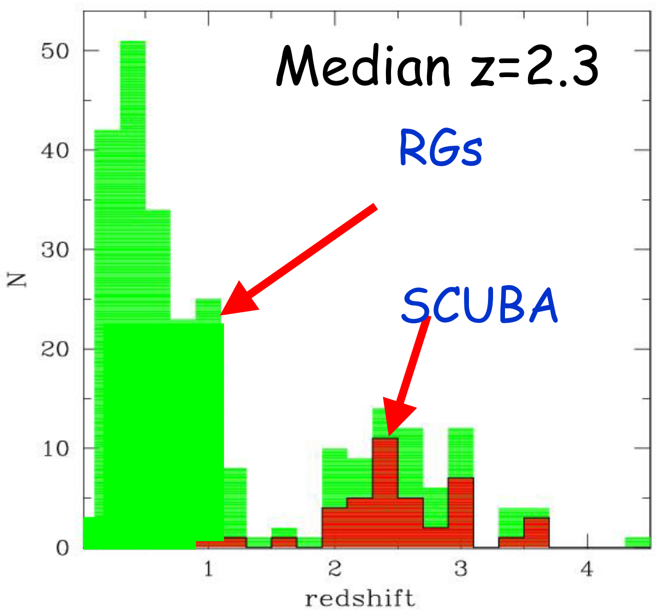
Keck 10m Spectroscopic Observations

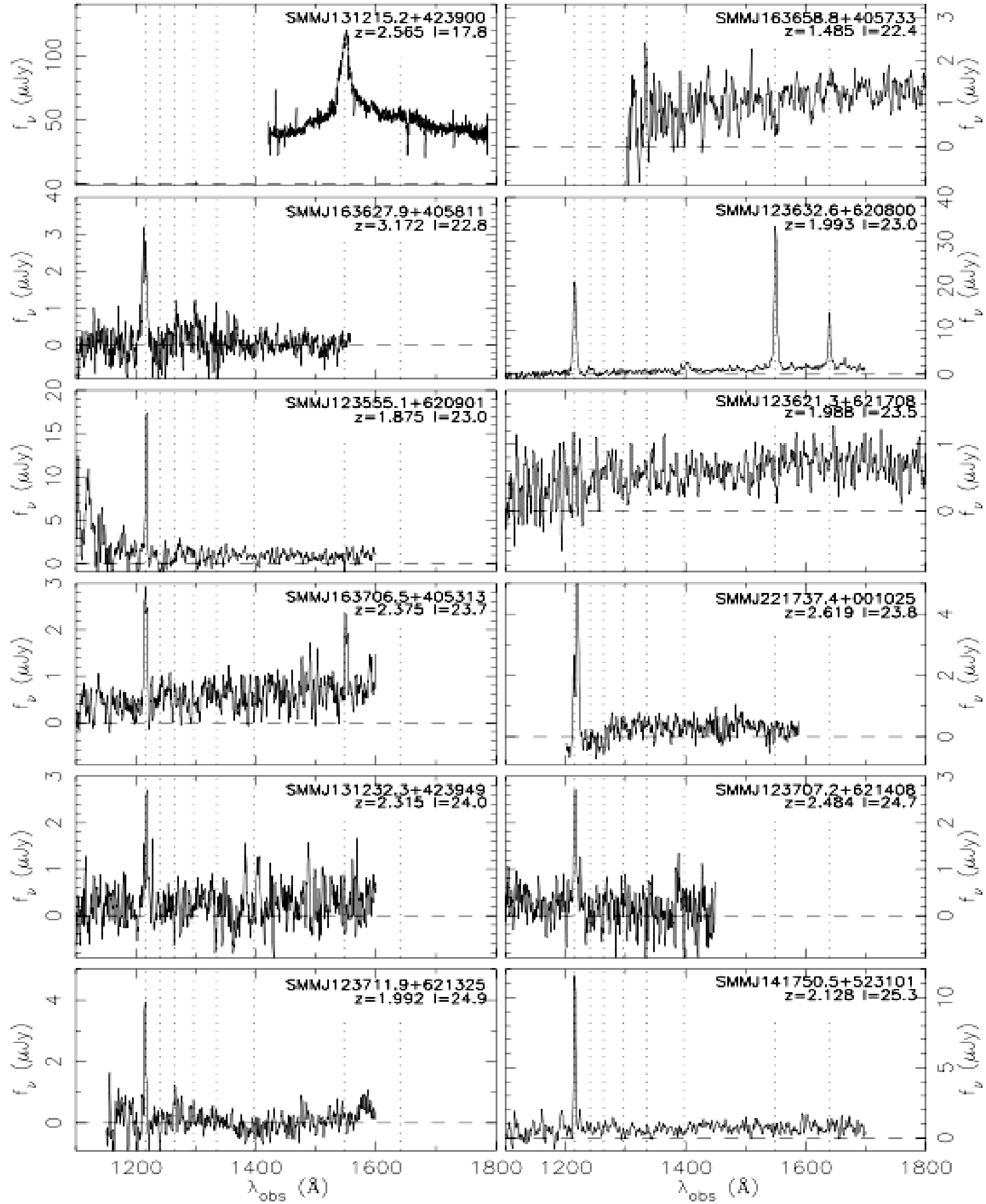
take these precise radio positions to Keck …

- Target sample 150 SMGs in 7 fields [HDF/Lock/SA13/N2/CFRS3+14/SA22]
  - I=22-27 counterparts (faint!)
- Ignore apparent magnitudes and just integrate with Keck…
- 2-4hr LRIS exposures, 8 nights
  - LRIS-B high-sensitivity to 3200A

Spectroscopic Redshifts for 100 SMGs

- Easier than expected: strong emission lines (50%) (especially Lyα)
- ~75% spectroscopic completeness (Chapman+03)

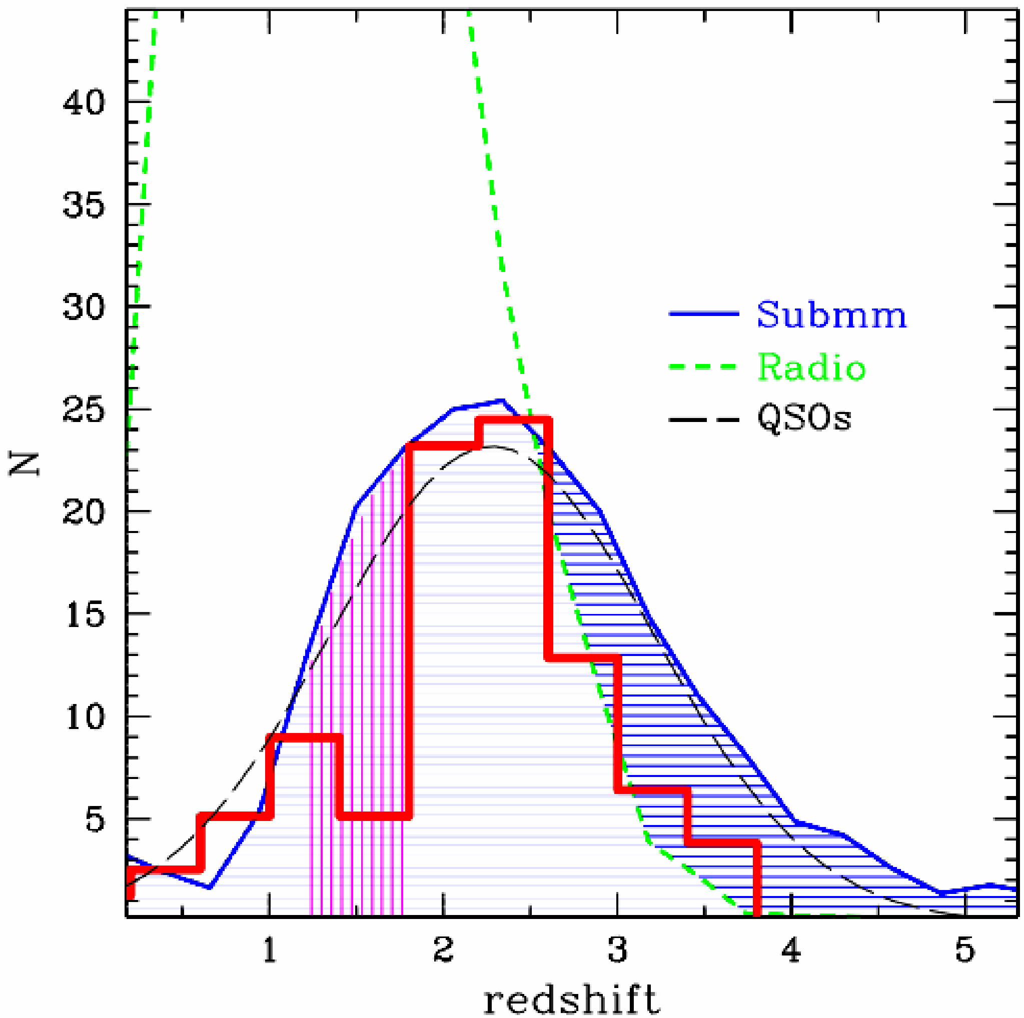




Median redshift for SCUBA galaxies

- Currently ~100 SMG z-IDs
- Median redshift z=2.3+/-0.4 full range z=1-4
- Use evolutionary models to understand selection effects
- Volume density ~10^{-5} Mpc^{-3} comparable to few M* Elliptic

(Chapman et al. 2003



High-z Galaxy Formation Themes

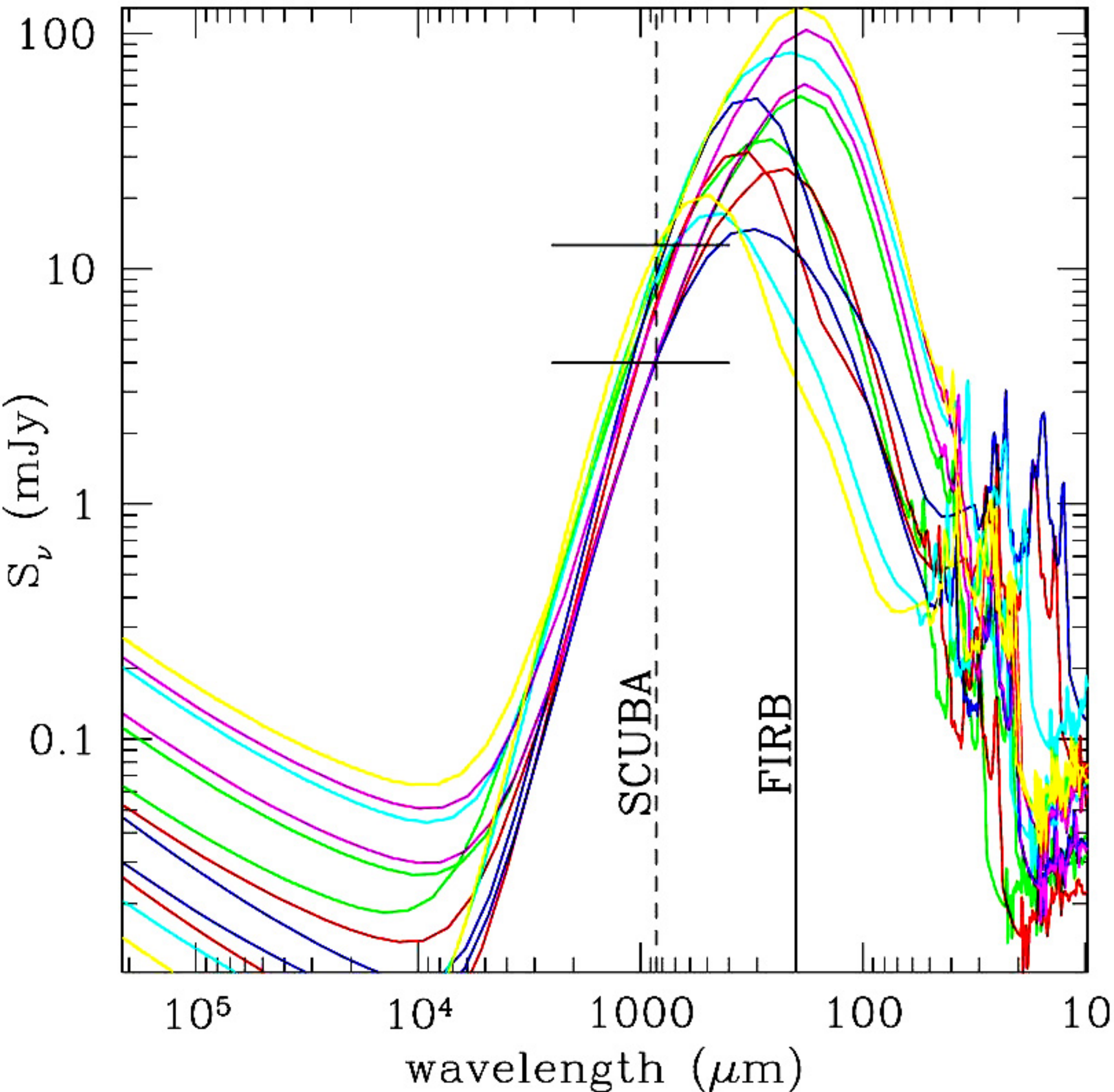
1) Broad range of dust temperatures/SEDs at high-z

2) What could we have learned from the UV
(are the SMGs/OFRGs orthogonal to BX/LBG?)

3) Once an AGN, always an AGN
AGN identified in the UV, is an AGN in the optical, and (locally) mid-IR
X-ray, radio?

4) SFRD evolution (the Madau plot)
Different Luminosity classes have different evolutions

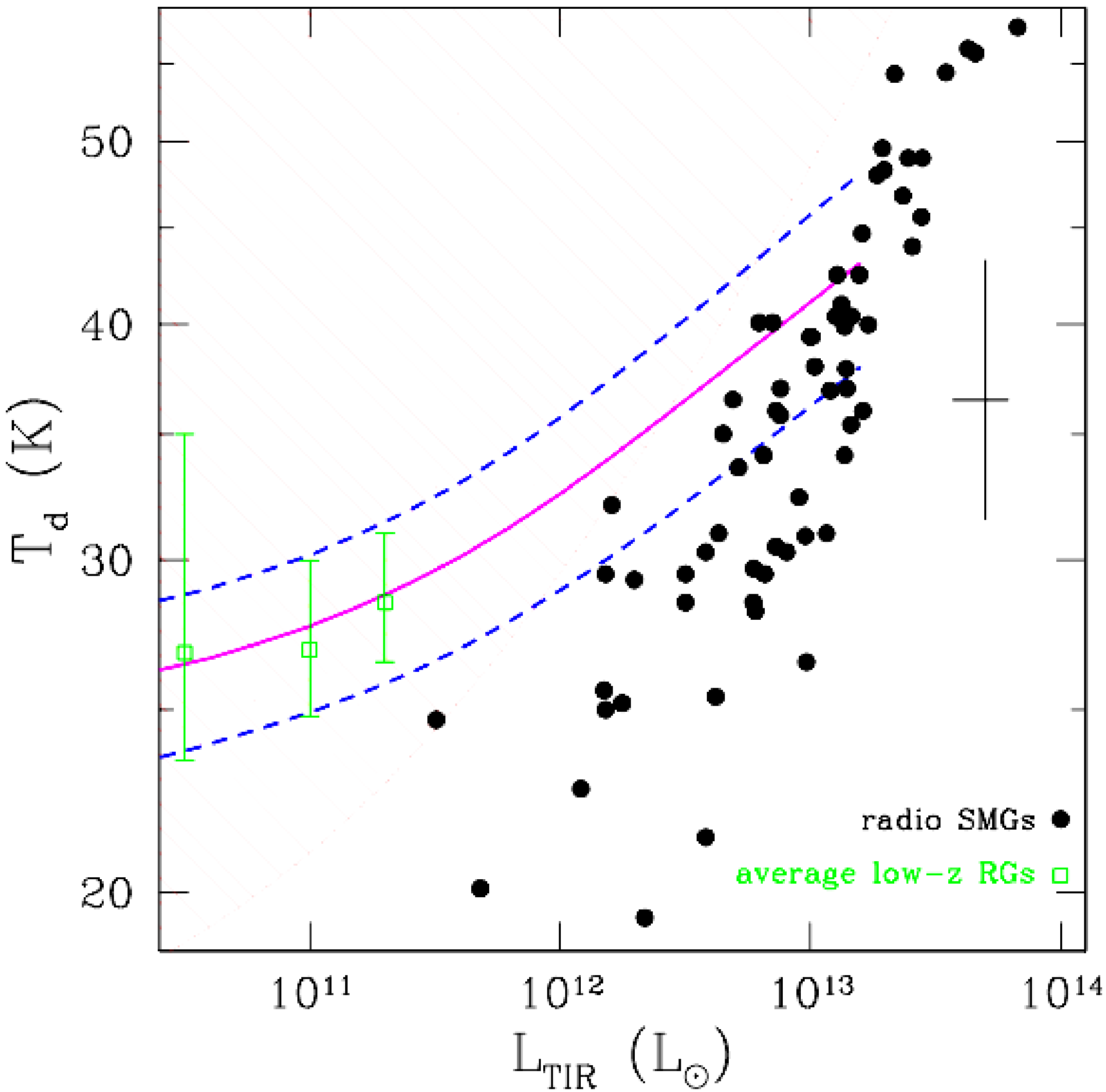
SCUBA galaxies – contribution to FIRB is small
Dust temperatures (Td=36K)



- Fit Dale+Helou (02) SEDs to 850, radio, z
- ***Confirm at 350um with SHARC2***

- *Spitzer* predictions PAHs, high-ion lines? Range >100@*24um* Hot dust?

Dust Temperatures (or SED shape)



- **Large range in dust temperatures**
(850μm luminosity doesn't reflect FIR)

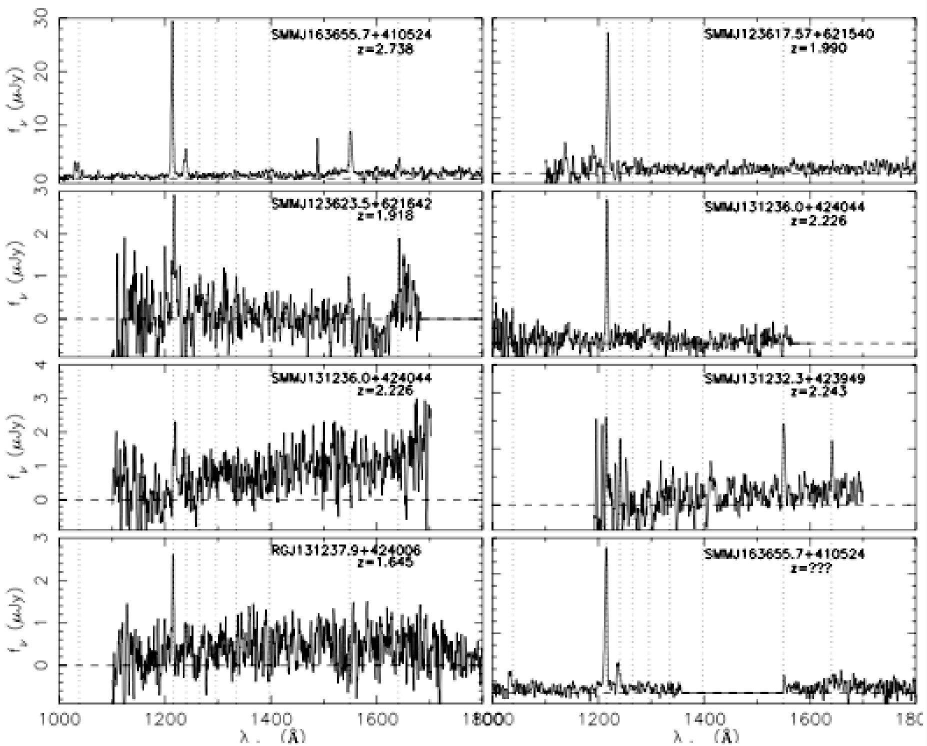
- 10 SMG
"Verified" Td, SHARC2, 350mu
(radio-FIR … IMF?)

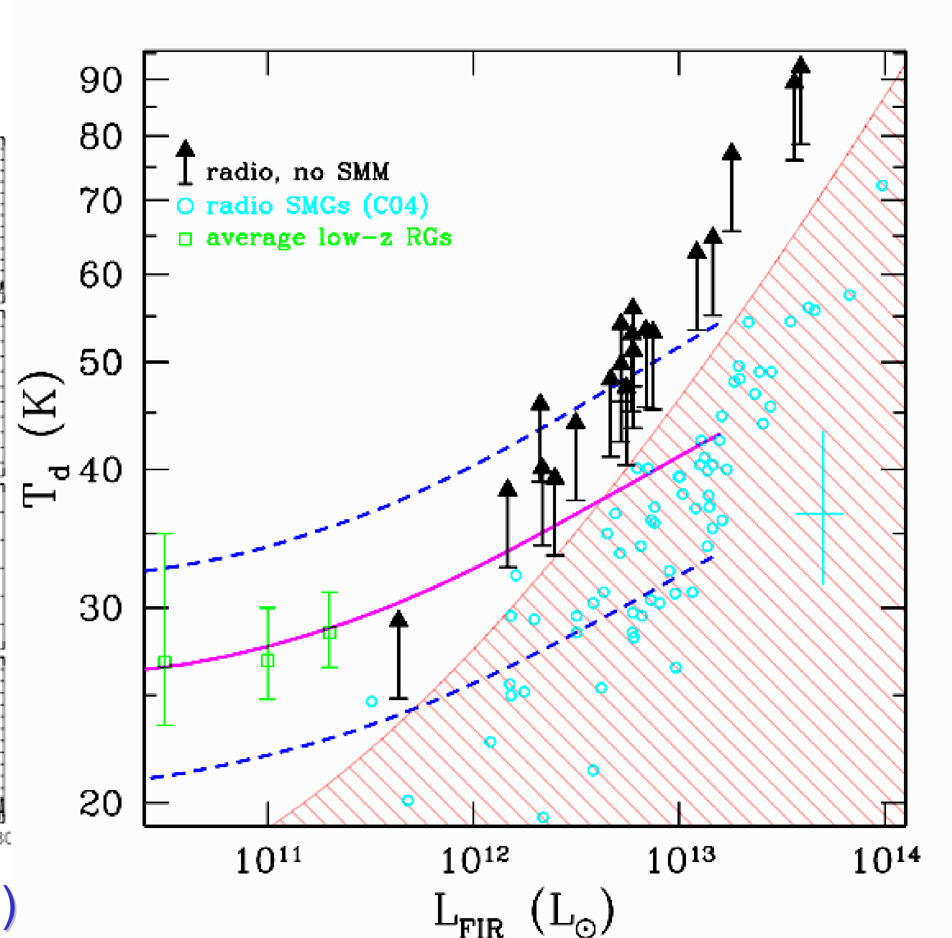
- **Calculate L_FIR & L_BOL**

… But, SMGs only **half** the story

OFRGs *(optically faint radio galaxies)*

All the FIR luminosity of SMGs; Undetected with SCUBA
Mostly Star Formers; Similar volume densities; hotter Td’s

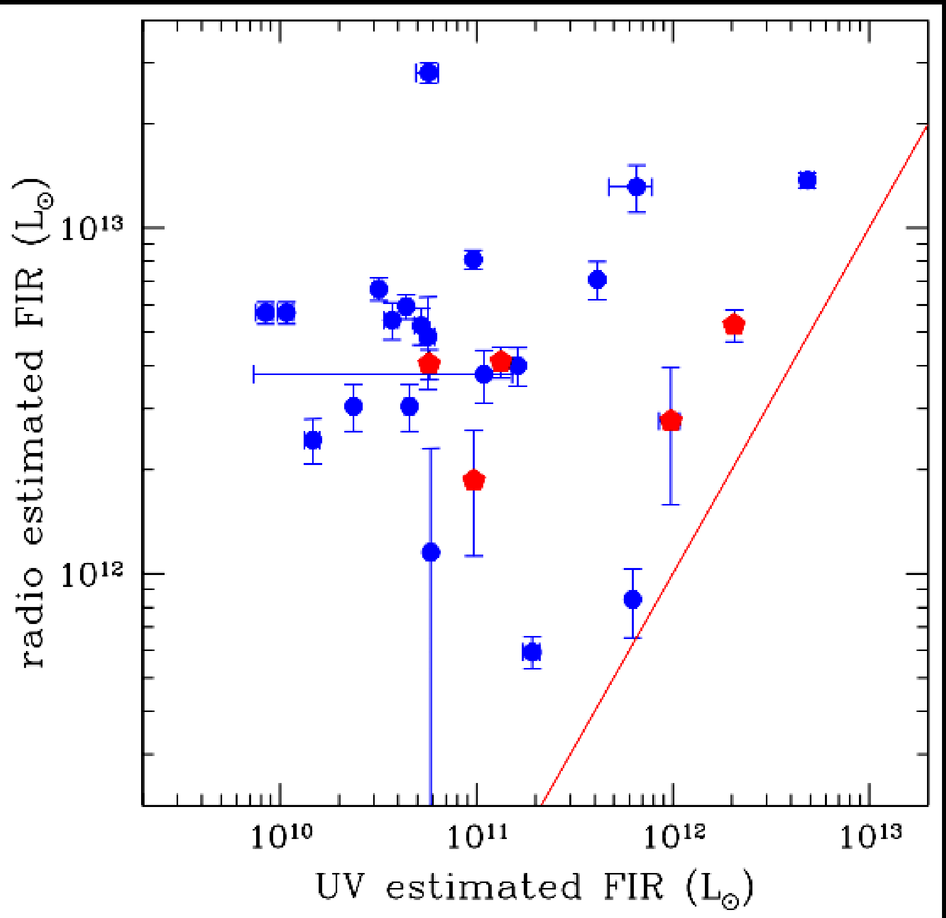




(Chapman et al 2004; Blain et al. 2004)

SMGs: what do we learn from UV?

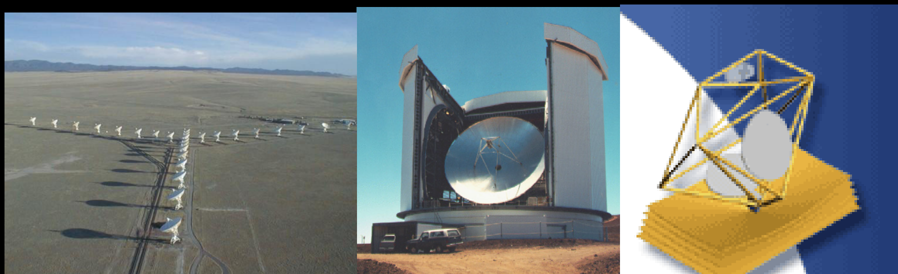
submm/radio versus U,B,R



-detect ‘most’ SMGs at *B,R,I,J,K* - bands

(many at U if *z*<2.7)

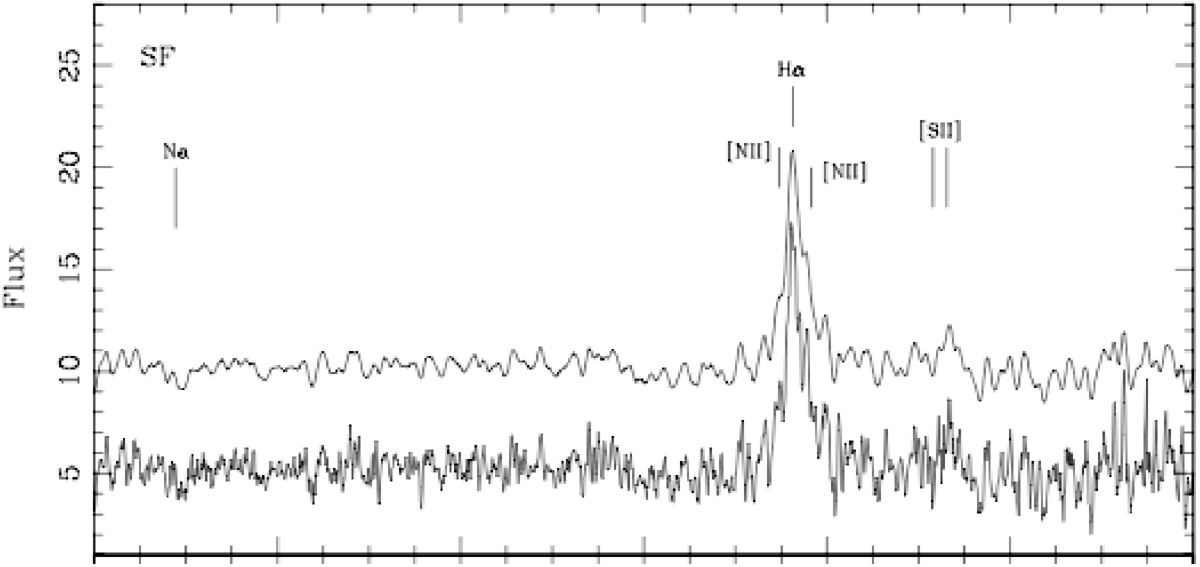
-but … FIR luminosities severely under-predicted



Hidden AGN?

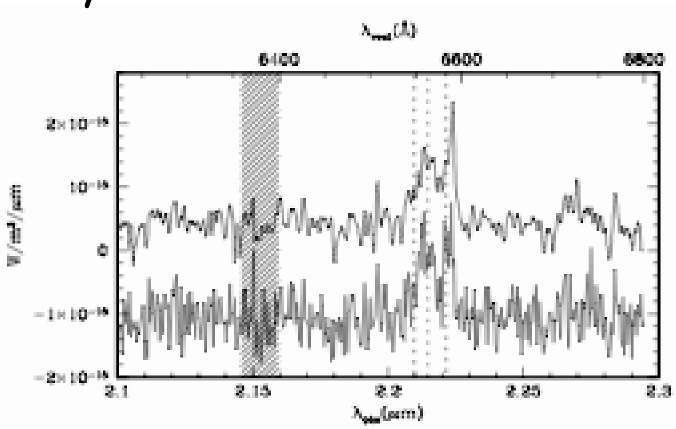
Nebular Line Emission: Composite Hα spectrum,

25 Hα detections; stack the 18 “starbursts”



- <FWHM>=450km/s
- No [OI]6300 detected
- Nii/Hα < 0.5 - SF

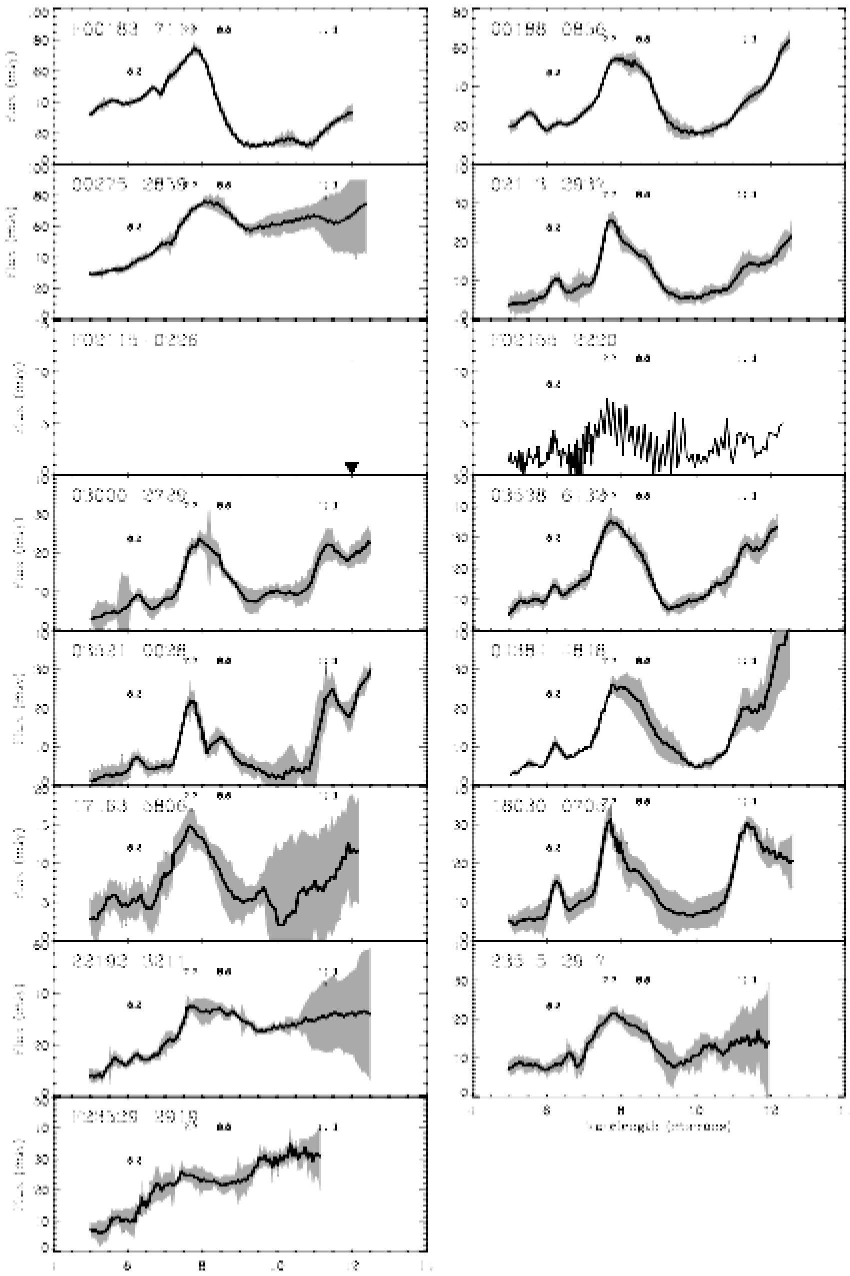
- X-ray & extended-radio => SCUBA galaxies *not* dominated by AGN



AGN in the UV,

AGN in Halpha

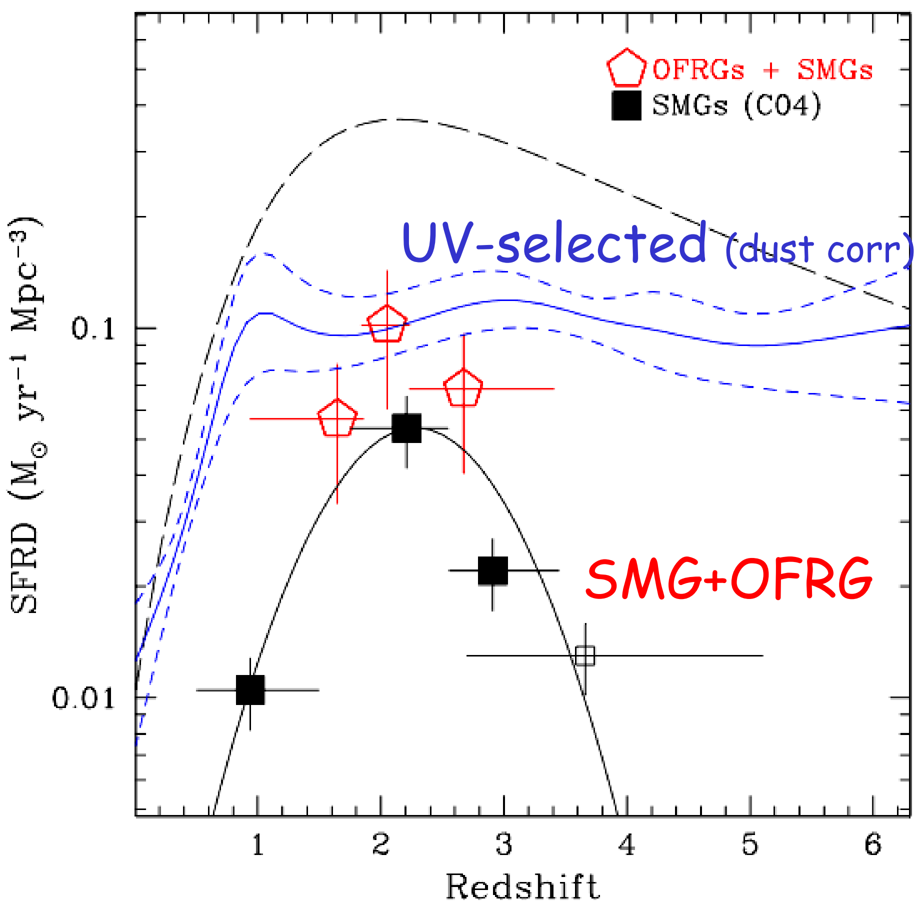
Spitzer - continuum phot; midIR spectroscopy



- SMGs detected at all Spitzer wavelengths - crude SB/AGN classification (Frayer+ 2004, Ivison+ 04, Egami+ 04)
- ...the promise of midIR spectroscopy (~1hr integrations with IRS?)
- HOWEVER:
  UV/optical classifications the same as mid-IR locally (PAHs vs power-law) (Tran et al. 2001; Lutz et al. 1999)

The Star Formation History of the Universe

- X-ray & extended-radio => SCUBA galaxies *not* dominated by AGN



UV galaxies
evolve differently from
Luminous FarIR galaxies

- SMG/OFRG : main site of massive star formation at z>2
- <M* galaxies assemble more gradually over long time.

- Balance between obscured and unobscured SF has shifted drastically in last 80% T_{Hub}

(Chapman et al. 2004)

Where are we, where do we go?

1) Currently only scratching the surface of luminous/massive galaxies (Spitzer and Herschel will help considerably)

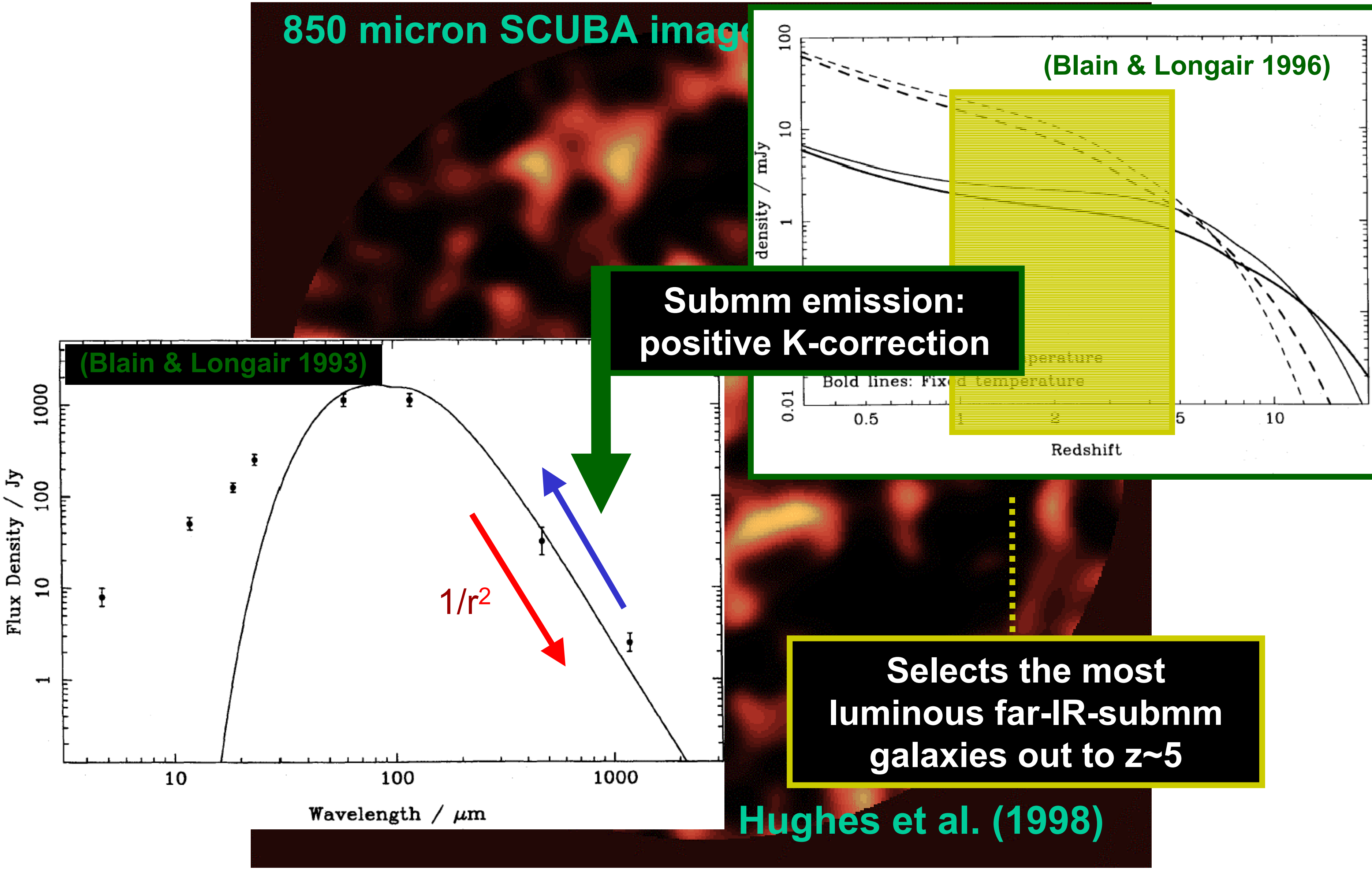
-still unsure if we have census of all z~2 luminous galaxies

2) To really understand galaxy formation and evolution (<M* galaxies), we need larger,colder facilities.

-finding the hyper-luminous peaks in different bands not enough.

-e.g., understand an individual galaxy's effects on IGM.

Submm Cosmology: power of the K-correction

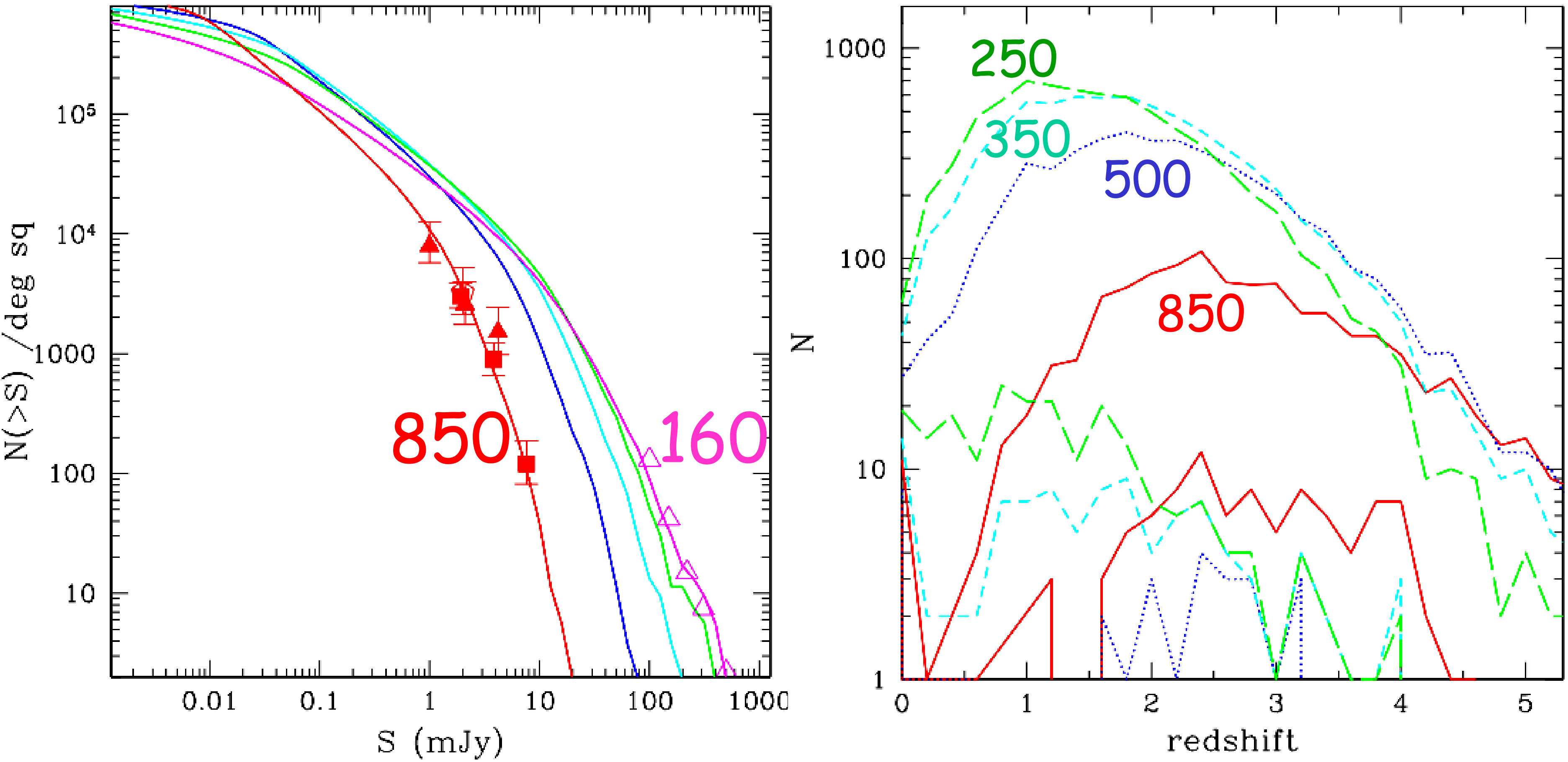


Submm Continuum from Space:

<350μm (still large beamsize on HERSCHEL) confusion limits to low-z galaxies

>350μm; higher-z galaxies: *but* confusion happens immediately

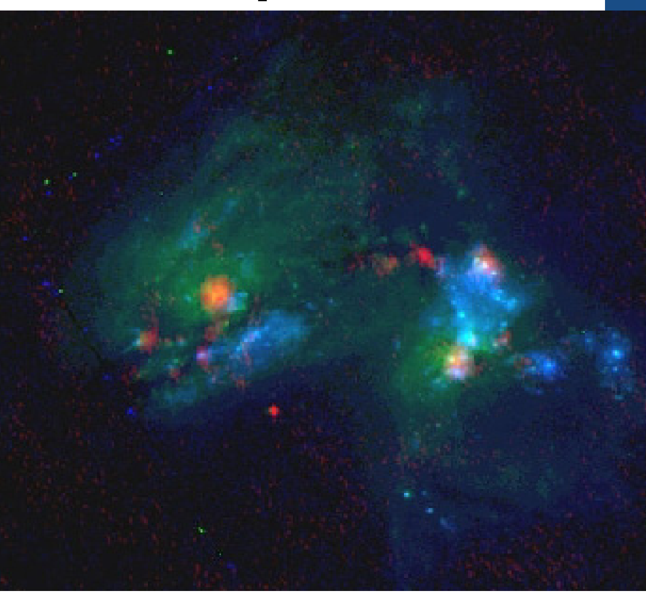
Bivariate LF (Chapman,Helou+03) to model Td distribution.



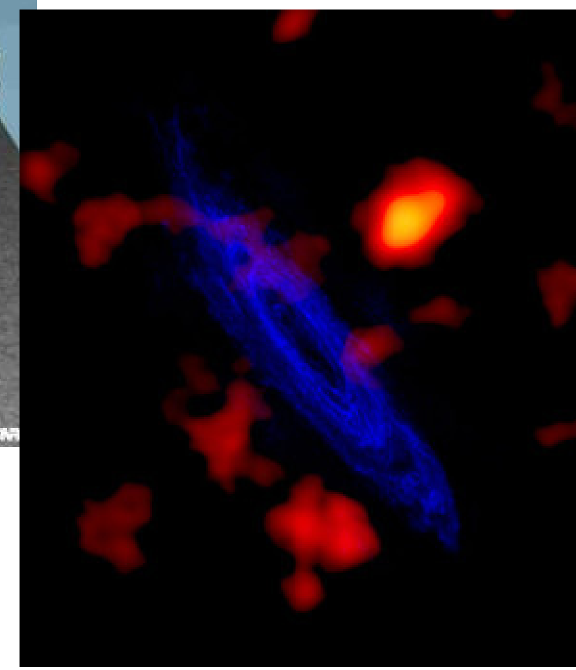
Expanded Very Large Array

EVLA

Arp299



Andromeda



EVLA: "far-IR" selection

- 10x more sensitive than VLA ...

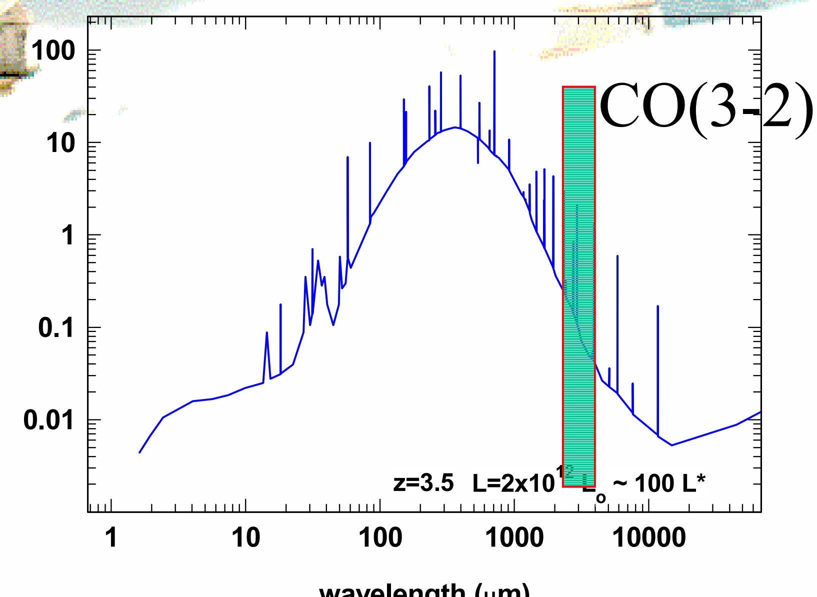
- new correlator, longer baselines, more antennas

Molecular/Fine Structure emission lines

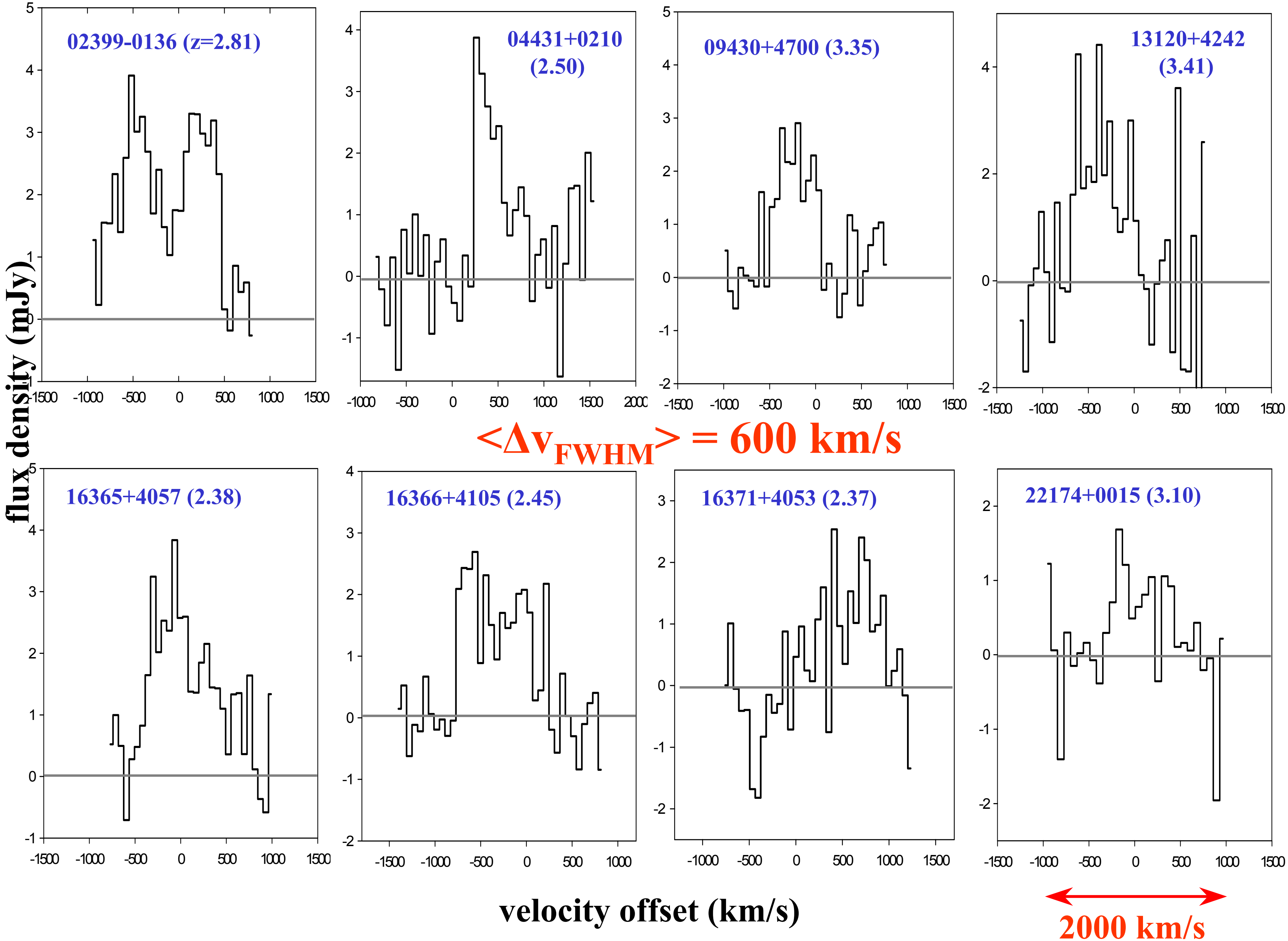
- Molecular gas *defines* sites of star formation
  - •IRAM-PdBI Needs precise redshifts (500Mhz band)
  - •17 SMGs observed, 12 detected in CO

    (Neri et al. 2003, Greve et al. 2004)

6x15m IRAM PdB Interferometer

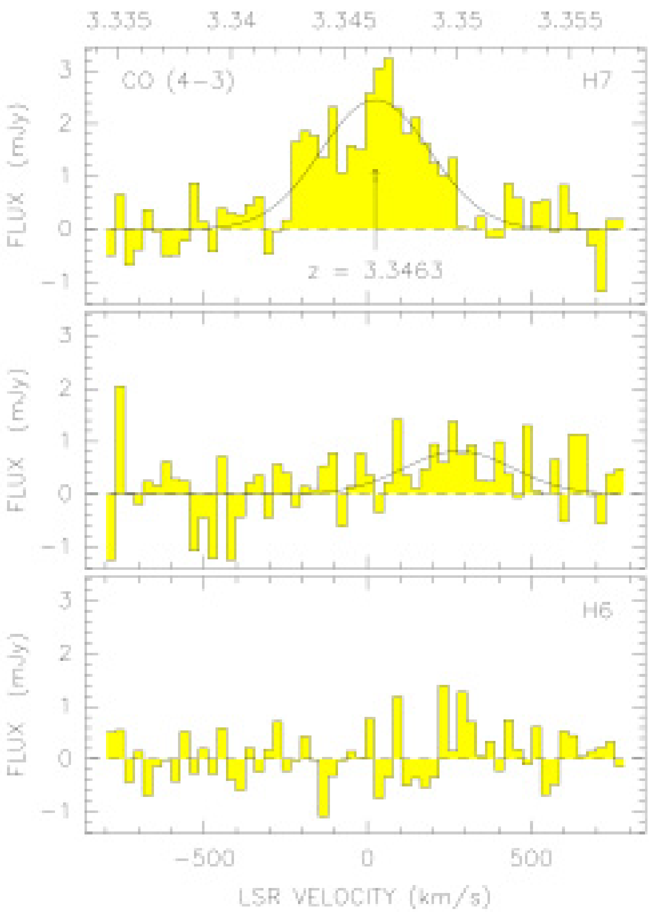


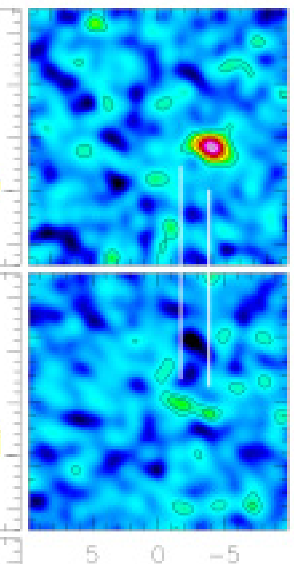
PdBI CO (3-2/4-3) Survey (stretching the limits of the facility!)



Longest baselines: High Spatial Resolution CO

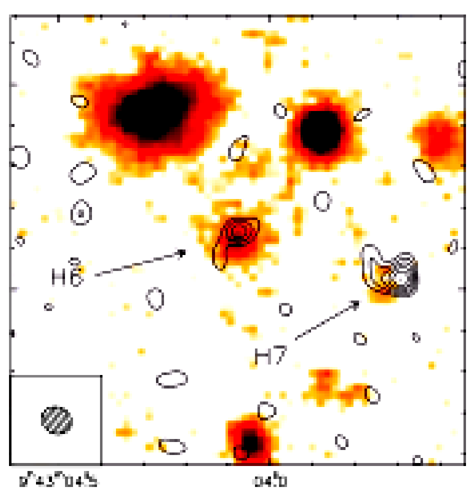
Z=3.4 SMG, H6/H7 (Neri et al. 2003)

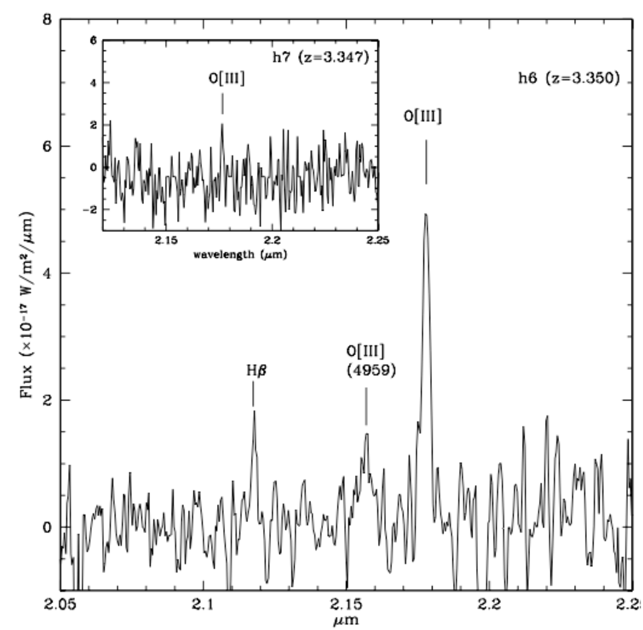




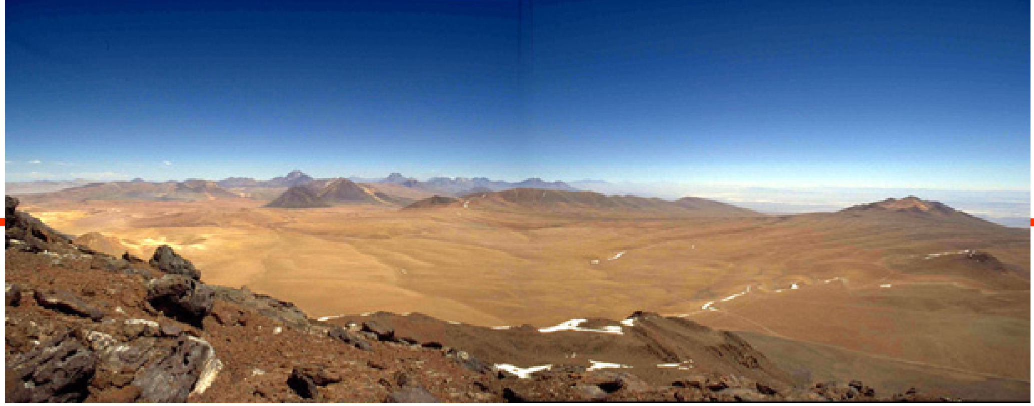
- 2 radio components
- both detected in mm
  - *1" synthesized beam*
- only H7 detected in CO

(but [OIII] confirms z's)

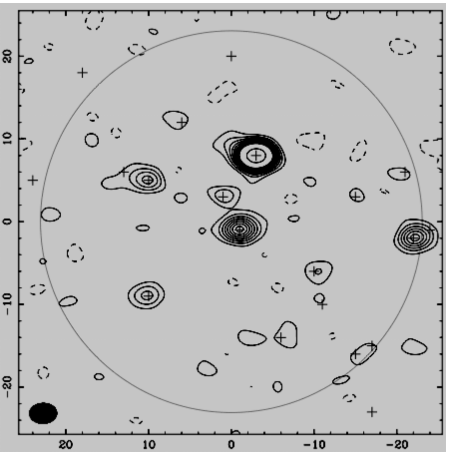


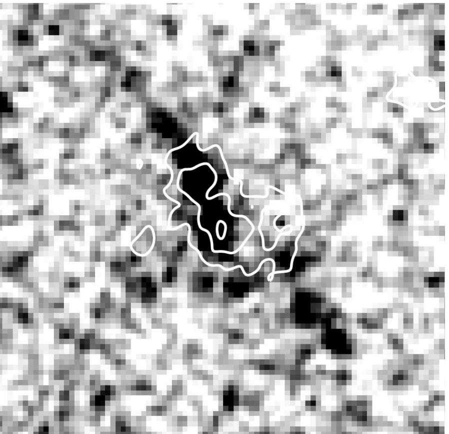


ALMA
ATACAMA LARGE MILLIMETER ARRAY

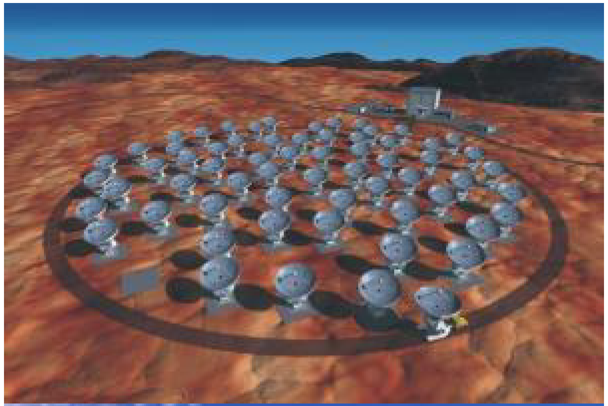


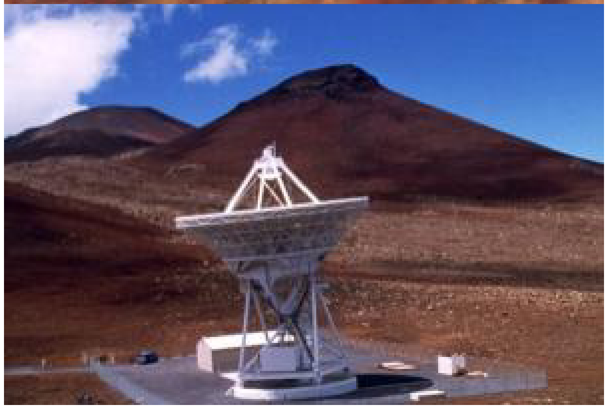
ALMA



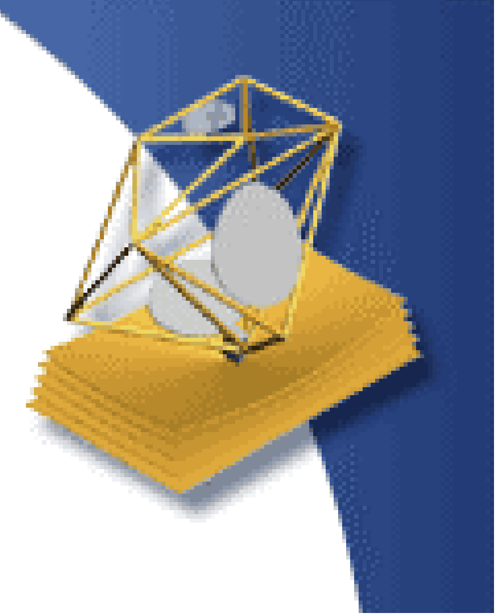


- Deep submm maps <1″ resolution
- CO-redshifts for all sources
- Detect MW-type galaxies out to high redshifts!





- Resolved structures (HST scales … sub-arcsec) in continuum, and in molecular & fine structure lines.



SAFIR: overcome 40μm confusion with aperture size!

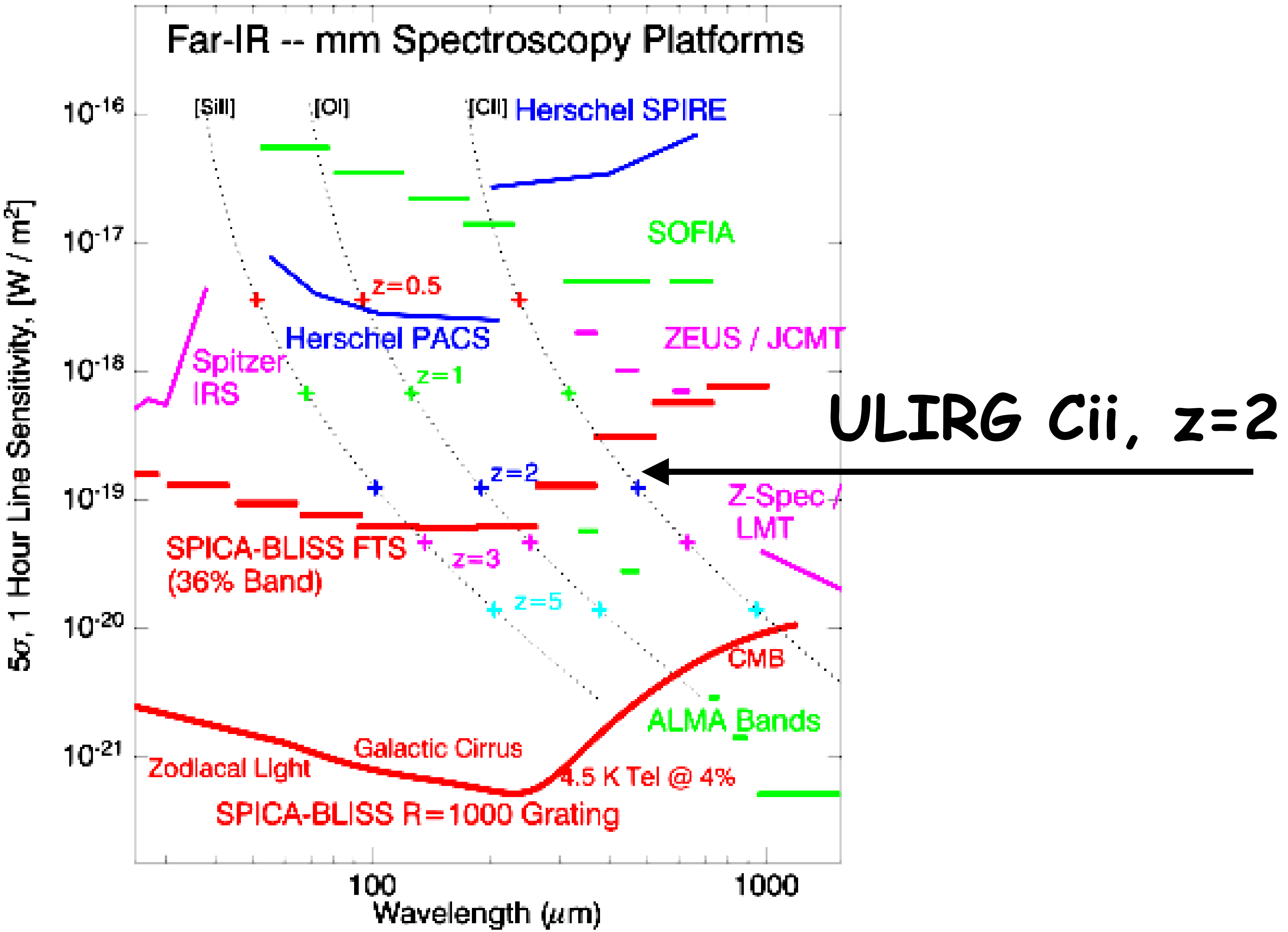
But in submm: pre-SAFIR …
SPICA/BLISS: cold (4.5K) 3.5m telescope (PI: M.Bradford)

Fine Structure Lines:

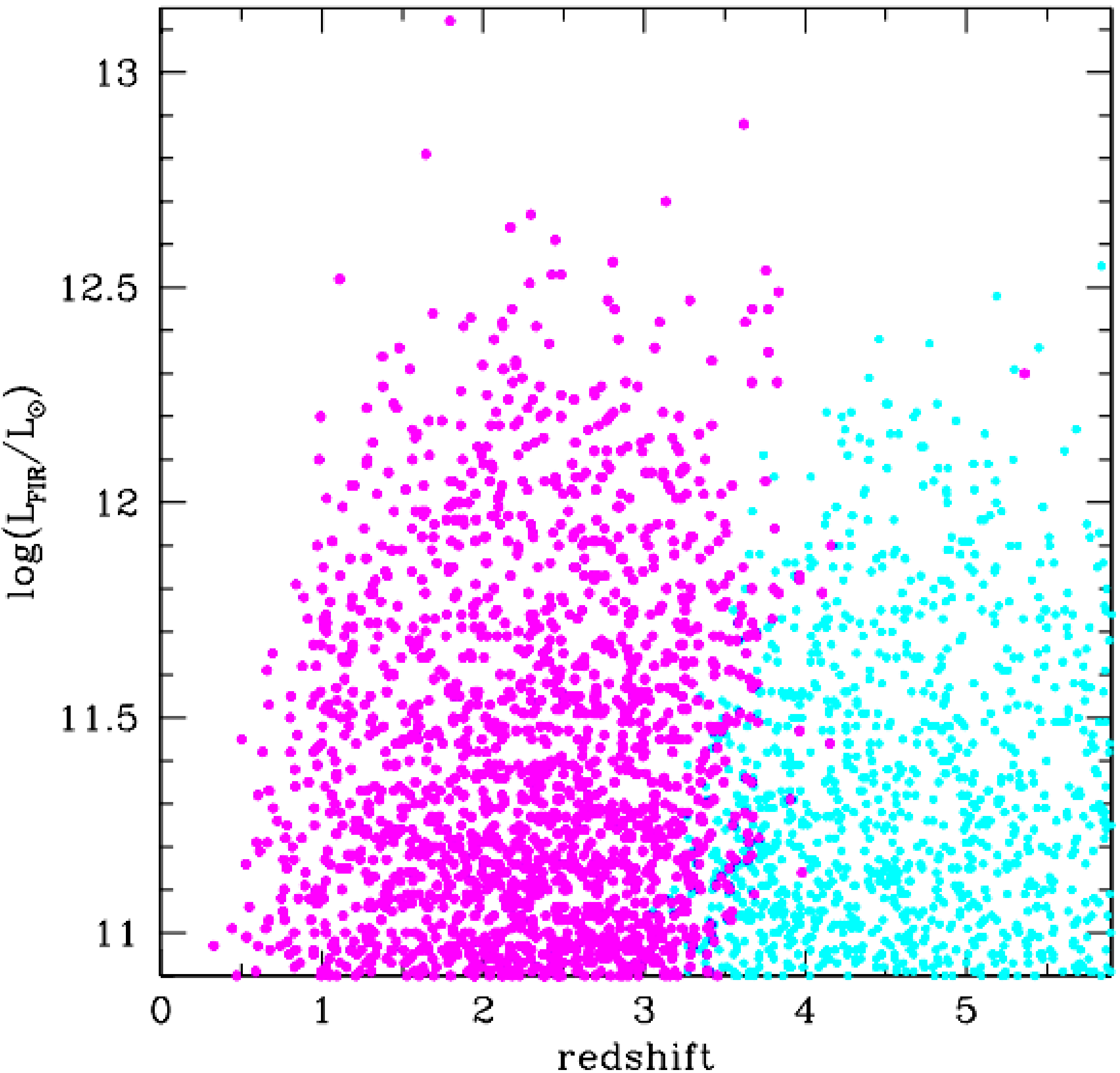
-overcoming confusion (bright, detectable lines)
-probing temperature, density, ionization state of material around luminosity source.

-couple to entire bulk of galaxy
(not just "skin" as optical lines)

Fine Structure Lines: COLD, 3.5m aperture



Fine Structure Lines: temperature range in FIR SEDs



Bivariate LF (Td,L)

(Chapman, Helou, Lewis, Dale 03)

Cii tied to PAH strength (Helou+ 01)

Temperature distribution implies a range of redshift detectability

CONCLUDE:
High-z Galaxy Formation Themes

1)Broad range of dust temperatures/SEDs at high-z
 -> detectability; luminosities; probe full FarIR SED to characterize

2) What could we have learned from the UV?
 -> need submm/farIR to identify luminous, enshrouded galaxies

3) Once an AGN, always an AGN
 -> Do AGN exist which are truly completely hidden?

4) Different Luminosity classes have different evolutions
 -> we want FarIR selection and fine structure line diagnostics, out to z>5 to understand how the complete mass spectrum of galaxies assembles

Conclusions

- SCUBA galaxies have many of the expected properties of proto-E's
  - Median z=2.4+/-0.4 for >5mJy SMGs, produce 20% EBL
  - Space density of ULIRGs ~1000x higher at z~2-3 than today
  - Space density comparable to massive E's at z=0
  - Striking merger-like morphologies
  - CO follow-up shows these are gas rich and massive galaxies
  - Presence of weak AGN in many SCUBA galaxies – SMBH
  - Evidence that SMGs are strongly cluster in 3-D
- …properties consistent with merger of gas-rich disks w/ small bulges…
- Balance between obscured/unobscured SF has reversed in last 10 Gyrs
- Future facilities
  - SIRTF – ULIRGs at z=1-2, more detailed SEDs and spectroscopy – dust properties
  - SCUBA2 – much bigger samples of z>2 ULIRGs (sky survey for ALMA)
  - ALMA – gas dynamics, morphologies, etc for MW @ z<5

The End